Low Metallicity Indicates that the Hypervelocity Star HE 0437–5439 was Ejected from the LMC[1]

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ABSTRACT

We measure the metallicity of the unusual hypervelocity star HE 0437–5439 from high resolution spectroscopy to be half-solar. We determine a spectral type of B2 IV-III for the star and derive an effective temperature T_{eff} = 21,500 $\pm$ 1,000 K and a surface gravity $\log(g) = 3.7 \pm 0.2$ (cgs). We also present BV time series photometry and find the star to be non-variable at the 0.02 mag level. We refine the magnitude of the hypervelocity star to $V = 16.36 \pm 0.04$ mag, with a color $B-V = -0.23 \pm 0.03$ mag, confirming its early-type nature. Our metallicity result establishes the origin of HE 0437–5439 in the Large Magellanic Cloud and implies the existence of a massive black hole somewhere in this galaxy.

Subject headings: galaxies: individual (LMC) — stellar dynamics — stars: abundances — stars: early type — stars: individual (HE 0437–5439)

[1]Based on observations made with the European Southern Observatory telescopes obtained from the ESO/ST-ECF Science Archive Facility and with the 1 meter Henrietta Swope telescope located at Las Campanas Observatory, Chile.

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1. Introduction

Hills (1988) first proposed the existence of hypervelocity stars (HVSs) as evidence for a supermassive black hole in the center of our Galaxy. According to his calculations, an encounter of a close binary with a supermassive black hole could disrupt the binary, capturing one of the stars and ejecting the other as a HVS with a velocity up to 4000 km s^{-1}. Observational evidence for such objects was first presented by Brown et al. (2005), who serendipitously discovered the first HVS, SDSS J090745.0+024507, in a survey of blue horizontal branch stars. Fuentes et al. (2006) resolved the degeneracy between luminosity and distance for this star by detecting variability and providing evidence for the main-sequence nature of the first HVS.

To date ten HVSs have been reported (Brown et al. 2007, Table 1) and of these, HE 0437–5439 stands out as the most enigmatic one. While the origin of the other nine is consistent with being ejected from the center of our Galaxy, HE 0437–5439 is suspected to have been ejected from the Large Magellanic Cloud (LMC). Edelmann et al. (2005) discovered this HVS during a spectroscopic follow-up of their sample of subluminous B-star candidates from the Hamburg/ESO survey (e.g. Christlieb et al. 2001). HE 0437–5439, with an estimated apparent magnitude of $V = 16.2 \pm 0.2$ mag, is the brightest HVS known. Edelmann et al. (2005) obtained two high resolution spectra, but with a low signal to noise (S/N) ratio ($\sim$20), finding it to be a main-sequence early B-type star consistent with solar metallicity. They measured a heliocentric radial velocity of $+723 \pm 3$ km s^{-1}, a rotational velocity of 54 ± 4 km s^{-1} and derived a distance of $d = 61 \pm 12$ kpc from the Galatic center, which is inconsistent with the spectral type of the star. While an early-type B-star has a main-sequence lifetime of 25-35 Myr, it requires 100 Myr to travel that distance at the measured radial velocity.

The authors therefore propose two possible explanations for this paradox: either HE 0437–5439 is a Galactic blue straggler or it originated from the LMC. They suggest measurements of the chemical abundance and proper motion of the star to distinguish between the two scenarios. Gualandris & Portegies Zwart (2007) discarded the blue straggler scenario claiming that a merger product would not live much longer than a main-sequence star of the same mass. Assuming HE 0437–5439 was ejected by a black hole in the LMC, they perform scattering simulations and conclude that a black hole mass ≥ 1000 $M_{\odot}$ is required to explain the velocity of HE 0437–5439.

Motivated by these intriguing scenarios, we set out to measure the metallicity of HE 0437–5439 and obtained photometry to search for variability. We describe our findings in the following sections of this Letter.

2. Photometry

We imaged HE 0437–5439 in Johnson B and V bands with the Direct CCD on the 1-m Swope telescope at Las Campanas Observatory, Chile. We monitored the star over six consecutive nights (UT 2006 July 17-22), for about 2 hours per night. The images were processed with standard IRAF[1] routines, following the same procedure as described in Bonanos (2007). The light curves of HE 0437–5439 and several reference stars of similar brightness in the field were extracted with the ISIS image subtraction package (Alard & Lupton 1998; Alard 2000) in each filter and converted to magnitudes, following Hartman et al. (2004). The B and V time series photometry for HE 0437–5439 and two of the reference stars are shown in Figure 1. There is no evidence for variability to a precision of 0.02 mag over the 6 nights. HE 0437–5439 is therefore not pulsating as SDSS J090745.0+024507 (Fuentes et al. 2006), and the scenario of a blue straggler consisting of a contact binary is also unlikely.

To calibrate the B and V magnitudes of HE 0437–5439, we performed aperture photometry on images obtained on the photometric night of UT 2006 July 19 and applied transformation coefficients derived by Bonanos (2007) for this night, measuring $V = 16.36 \pm 0.04$ mag, $B-V = -0.23 \pm 0.03$ mag. This improves the photometry measured by Edelmann et al. (2005) from the Hamburg/ESO plates ($V = 16.2 \pm 0.2$ mag). The $B - V$ color we measure is consistent with that of an early-type B star. We note that the foreground extinction estimate from Schlegel et al. (1998) is $E(B - V) = 0.008$ mag, therefore the true unreddened V_0 and $(B - V)_0$ values are identical within the errors.

3. Spectroscopy

We retrieved public, unpublished spectra of HE 0437–5439 from the ESO archive. The data were obtained on UT 2006 January 12 with the Ultraviolet and Visual Echelle Spectrograph (UVES) on the VLT UT2 8-meter telescope (Kueyen) at the ESO Paranal Observatory. The observations consist of $8 \times 1482\,s$ and $1 \times 1810\,s$ spectra, with a resolving power $R \sim 34,000$, measured from the full width half maximum of the comparison lamp lines. We bias subtracted and flatfielded the spectra with the IRAF echelle package routines. We used the algorithm of Pych (2004) to remove cosmic rays from each two dimensional image. Next, we extracted the spectra, averaged them (weighting by the exposure time), normalized and merged the orders. The final spectrum ranges from 3746-4990 Å and has an average S/N

[1]IRAF is distributed by the National Optical Astronomy Observatory, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

ratio of ∼100.

We classify HE 0437–5439 as a B2 IV-III star according to the criteria defined by Walborn & Fitzpatrick (1990). The depths of the Si lines constrain the spectral type to B1-B2. Furthermore, Si III $\lambda 4552 >$ Si IV $\lambda 4089$ and Si II $\lambda\lambda 4128$-30 $<$ Si III $\lambda 4552$, while the O II blends at $\lambda 4640$ and $\lambda 4650$ have near equal depths, in support of a B2 type (C III lines affect the relative depths in B1 types). The luminosity class criteria are based on the relative strengths of the He I and Si III lines: He I $\lambda 4387$/Si III $\lambda 4552 \sim 5$, corresponding to IV, and He I $\lambda\lambda 4144/4121 \sim 2$, corresponding to IV-III. Our adopted spectral type, B2 IV-III, gives a slightly more evolved star than what Edelmann et al. (2005) found from their much lower quality spectrum.

4. Metallicity and Parameter Determination

We derived the metallicity and atmospheric parameters of HE 0437–5439 using the non-LTE Tlusty model atmosphere grid (Hubeny & Lanz 1995) described by Dufton et al. (2005) [2], which is appropriate for the analysis of B-type stars. The results for the parameters (effective temperatures, $T_{\rm eff}$; surface gravity, g, in units of cm s^{-2}; microturbulence, ξ; projected rotational velocity, $v \sin i$) and chemical abundance of HE 0437–5439 are presented in Table 1. We estimated the effective temperature from the ionization balance of Si II to Si III, the surface gravity from fitting the wings of the Balmer lines and the microturbulence from minimizing the scatter in the abundances of the Si III triplet of lines at 4560Å. The projected rotational velocity of the star was estimated by fitting rotationally broadened theoretical profiles to 14 strong metal lines and a mean value of 55 ± 1 km s^{-1} was obtained. The fits of rotationally broadened profiles to the Balmer lines are shown in Figure 2.

To derive the abundances, we measured the equivalent widths of the metal absorption lines (C, N, O, Mg and Si). The associated errors were calculated following the methods of Hunter et al. (2007) and include both random errors (measurement and atomic data uncertainties) and systematic errors from the adopted atmospheric parameters. We adopted the following uncertainties: 1,000 K in effective temperature, 0.2 dex in surface gravity and 3 km s^{-1} in microturbulence (for further details see Hunter et al. 2007). Table 1 gives in parentheses the number of lines used for each element. Further, it lists the LMC baseline abundance ($Z = 0.5\,Z_{\odot}$) from Hunter et al. (2007) and the baseline solar abundances from Asplund et al. (2005), for comparison. Our analysis follows identical methods to Hunter et al. (2007), i.e. we use the same absorption lines, atomic data and techniques

[2] See also http://star.pst.qub.ac.uk

and hence our abundance neasurements are directly comparable. The carbon abundance from the 4267Å line has been corrected by 0.34 dex following their method. The reason for this correction is that the carbon model atom used in the adopted TLUSTY model atmosphere grid is relatively simple compared to that used in more detailed analyses (e.g., Sigut 1996; Nieva & Przybilla 2006, 2007) and leads to a discrepancy between the carbon abundance derived from the 4267Å line and that from H II regions (Hunter et al. 2007). The correction is dependent upon the atmospheric parameters and we therefore note that while our absolute carbon abundance should be treated with caution, it is comparable with the LMC stars analysed by Hunter et al. (2007). The adopted metallicity of the grid (LMC in this case) has a negligible effect on the derived abundances (< 0.10 dex, from Hunter et al. 2007). The mild nitrogen enrichement is not uncommon as the enrichment of core processed material has often been observed in B-type stars (see for example Walborn 1970; Dufton 1972; Gies & Lambert 1992; Dufton et al. 2005; Korn et al. 2002; Venn 1999). In Figure 3, we plot representative metal lines used to determine abundances, along with TLUSTY model spectra at solar and half-solar metallicities, showing that the half-solar metallicity model correctly reproduces the metal lines. Clearly, the chemical abundance derived for HE 0437–5439 indicates an origin from the LMC.

We estimate a slightly higher mass of $9.0 \pm 0.5\ M_{\odot}$ for HE 0437–5439 than Edelmann et al. (2005, see their Figure 3), using our new parameters and the evolutionary models of Schaerer et al. (1993). We also recalculate the distance to HE 0437–5439 following Edelmann et al. (2005). With the new values for the magnitude, mass and surface gravity we obtain a longer distance of 73^{+6}_{-5} kpc. A star of this mass, B2 IV-III spectral type and LMC metallicity should have an age less than the value estimated by Edelmann et al. (2005) for an $8\,\mathrm{M}_{\odot}$ main-sequence early-B star at this metallicity, i.e. 35 Myr. Using the best fit TLUSTY model spectrum, we confirm the radial velocity of the star to be 723 ± 2 km s^{-1} with the IRAF *rvsao.xcsao* task. We note that HE 0437–5439 is the only HVS so far with an accurate rotational velocity measurement: 55 ± 1 km s^{-1}. Hansen (2007) predicted that the rotational velocities of HVSs ejected by the Hills (1988) scenario (originating in binaries) should be lower than those of single stars of the same spectral type. Our measurement confirms a low $v \sin i$ for HE 0437–5439.

5. Discussion

We measure the chemical abundance of the hypervelocity star HE 0437–5439 and find that it has half-solar metallicity, thus establishing its origin in the LMC. We can therefore rule out Galactic origin, because stars in the Galactic center have been found to have solar

or supersolar metallicities (e.g. Carr et al. 2000; Ramírez et al. 2000; Najarro et al. 2004; Wang et al. 2006; Cunha et al. 2007). A scenario of ejection from the low-metallicity outskirts of the Galactic disk also suffers from the age paradox (see Figure 4 in Edelmann et al. 2005). Our non-variable photometry further renders a scenario with a contact binary blue straggler ejected from our Galaxy unlikely.

HE 0437–5439 must therefore have been ejected from the LMC. A noteworthy implication of our result is the existence of a massive black hole in the LMC, as suggested by Gualandris & Portegies Zwart (2007). According to the simulations these authors performed, an intermediate mass black hole (IMBH) of mass $\geq 1000\,\mathrm{M}_{\odot}$ is required to eject HE 0437–5439 from the LMC. A three-body interaction involving a stellar mass black hole, while still possible, is very unlikely. Gualandris & Portegies Zwart (2007) find NGC 2004 and NGC 2100 to be the best candidate hosts of an IMBH in the LMC, based on criteria of age, density and mass. Further work is necessary to determine the location of the massive black hole in the LMC.

In summary, by establishing the origin of HE 0437–5439, we find dynamical evidence for the existence of a hitherto undetected massive black hole in the LMC.

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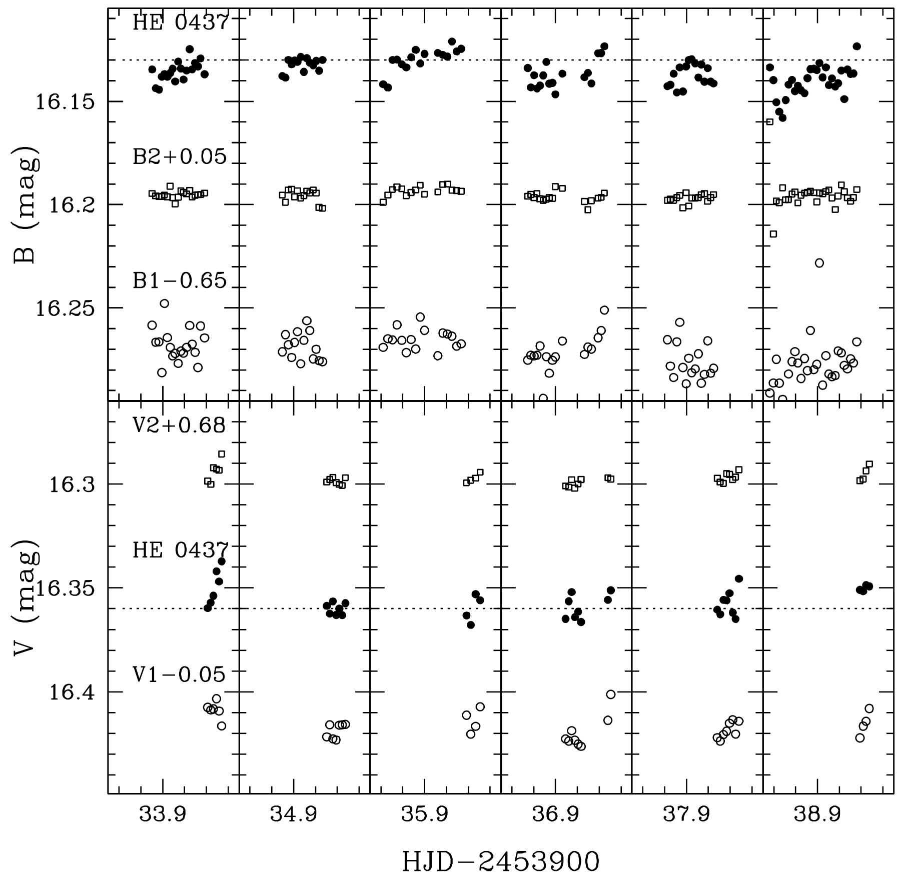

Fig. 1.— B and V−band light curves of HE 0437–5439 (*filled circles*) and 2 other comparison stars of similar brightness, shifted for display purposes. Panels correspond to each of the six consecutive nights of observation; tickmarks on the x-axis correspond to 0.02 day intervals. Dotted lines indicate the absolute photometry derived from the second, photometric night: $V = 16.36 \pm 0.04$ mag, $B - V = -0.23 \pm 0.03$ mag.

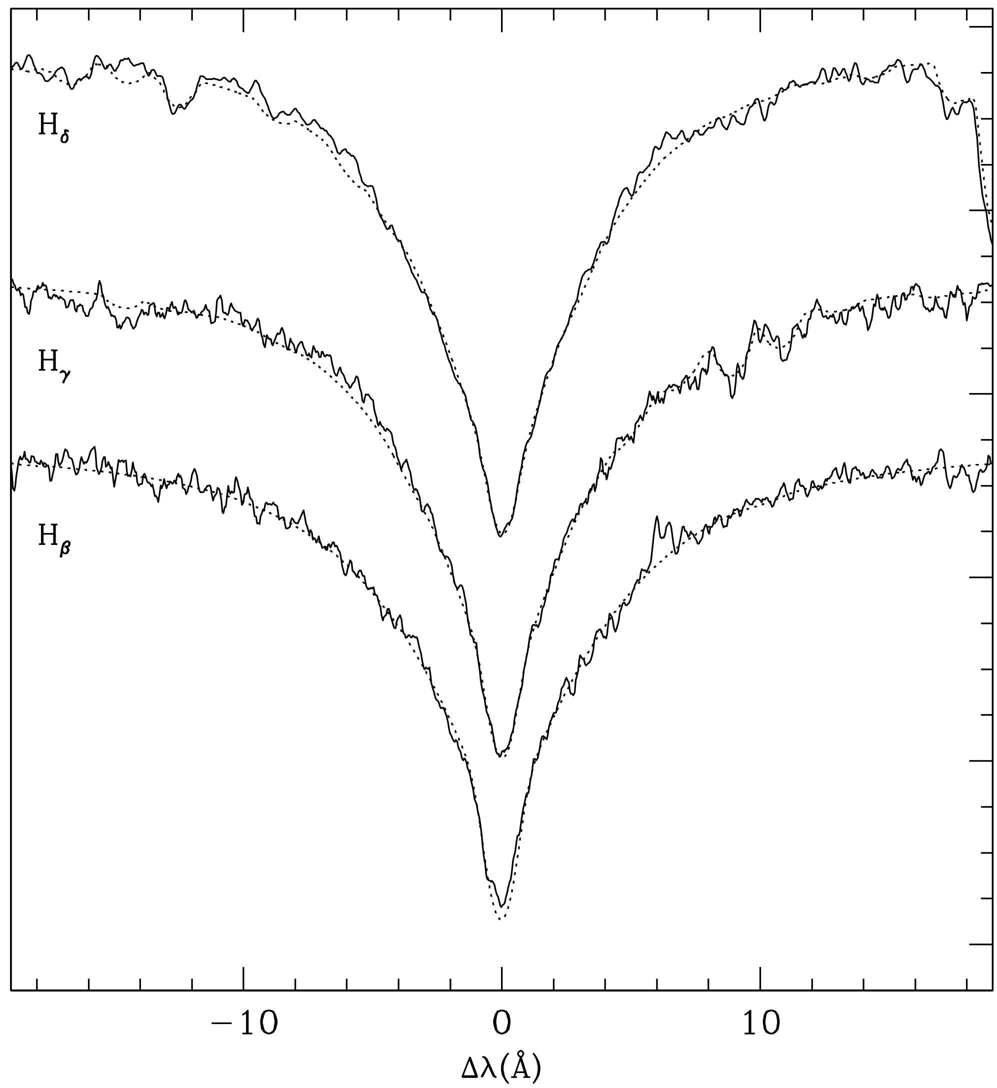

Fig. 2.— Balmer lines of HE 0437–5439. The TLUSTY model spectrum (dotted line) for the derived parameters is overplotted, illustrating the good fit to the Balmer wings.

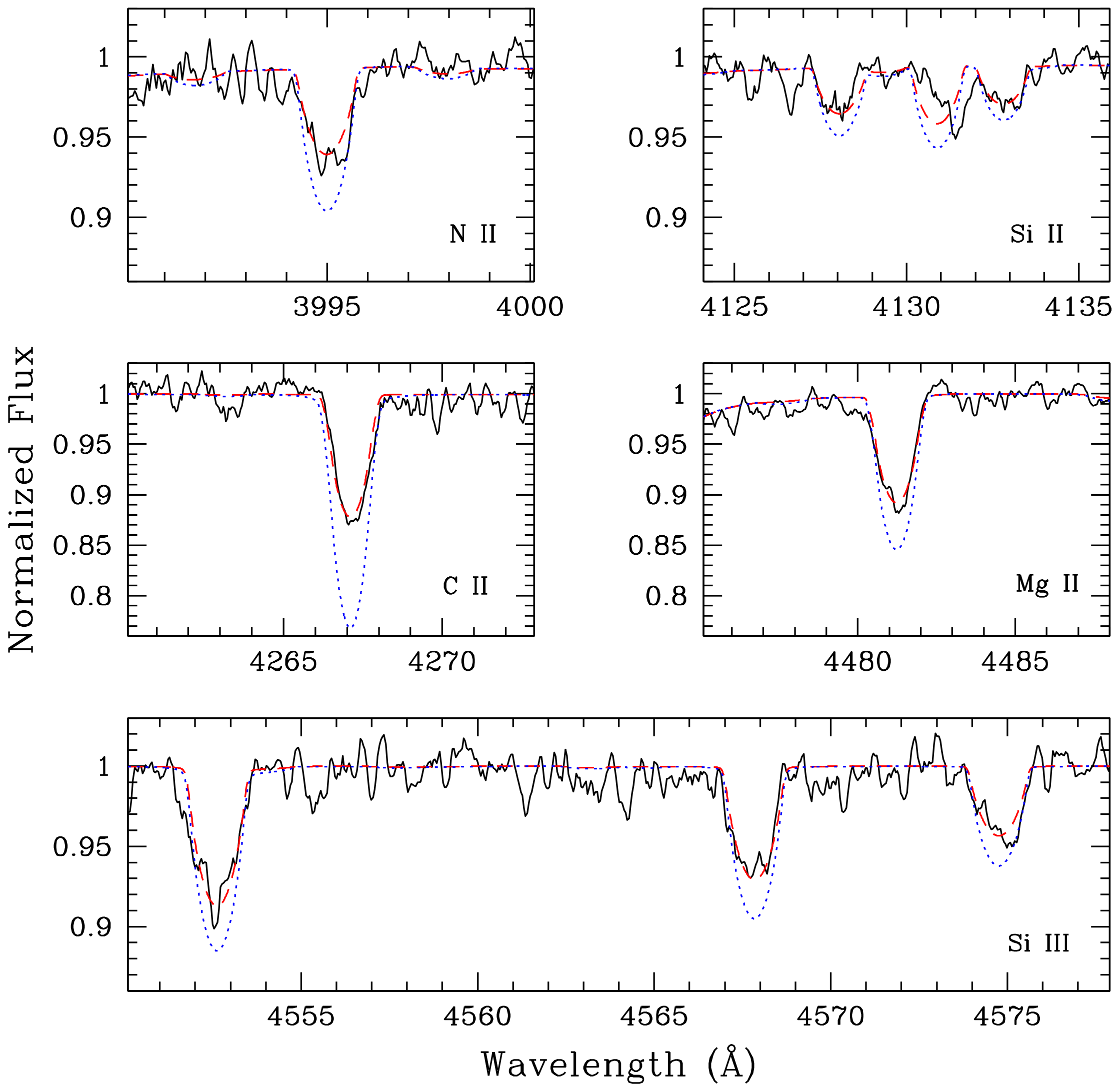

Fig. 3.— Representative metal lines in HE 0437–5439 (solid line) used to derive abundances. TLUSTY model spectra for half-solar (dashed line) and solar (dotted line) metallicity are overplotted, illustrating that the metallicity of HE 0437–5439 is half-solar.

Table 1. Parameters and Abundances For HE 0437–5439[a].

Parameter	HE 0437–5439	LMC Abund.	Solar Abund.
$T_{\rm eff}$ (K)	21,500± 1,000		
$\log(g)$ (dex)	3.70 ±0.2		
ξ (km s^{-1})	2±3		
$v \sin i$ (km s^{-1})	55±1		
C II	7.79±0.13 (1)	7.75	8.39
N II	7.30±0.24 (1)	6.90	7.78
O II	8.44±0.33 (13)	8.35	8.66
Mg II	7.10±0.18 (1)	7.05	7.53
Si II	7.17±0.21 (2)	7.20	7.51
Si III	7.18±0.34 (3)	7.20	7.51

[a]See §4 for details.

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